Phys. Lett. B 865 (2025) 139466

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Letter

First polarisation measurement of coherently photoproduced J/ψ in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

ALICE Collaboration *

ARTICLE INFO

Editor: M. Doser

ABSTRACT

The first measurement of the polarisation of coherently photoproduced J/ψ mesons in ultra-peripheral Pb–Pb collisions, using data at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, is presented. The J/ψ meson is measured via its dimuon decay channel in the forward rapidity interval $-4.0 < y < -2.5$ using the ALICE detector at the CERN LHC. An event sample corresponding to an integrated luminosity of 750 μb^{-1} ± 5% (syst) is analysed. Hadronic activity is highly suppressed since the interaction is mediated by a photon. The polar and azimuthal angle distributions of the decay muons are measured, and the polarisation parameters λ_θ, λ_φ, $\lambda_{\theta\varphi}$ are extracted. The analysis is carried out in the helicity frame. The results are found to be consistent with a transversely polarised J/ψ. These values are compared with previous measurements by the H1 and ZEUS experiments. The polarisation parameters of coherent J/ψ photoproduction in Pb–Pb collisions are found to be consistent with the s-channel helicity conservation hypothesis.

1. Introduction

The study of vector meson photoproduction at high energies has received great interest in recent years [1–3]. Ultra-peripheral collisions (UPCs) at the CERN Large Hadron Collider (LHC) allow access to the highest available photon energies for such photon–induced interactions. In UPCs, the impact parameter is larger than the sum of the radii of the two colliding nuclei, so they are beyond the range of the nuclear force and do not interact hadronically. A quasi-real photon is emitted from one of the charged nuclei and this in turn might fluctuate into a quark–antiquark pair, which can scatter elastically off the other nucleus. Vector meson photoproduction off nuclei can be either coherent, with the photon coupling coherently to the nucleus as a whole, or incoherent, where instead the photon couples to a single nucleon. Much emphasis has been put on how this process could give access to space and momentum features of the momentum distribution of gluons of the hadronic target. In particular, several model calculations indicate that vector meson photoproduction is sensitive to nuclear modifications of the partonic structure for gluons that carry a rather small fraction of the momentum of the nucleons [4,5]. Kinematics dictates that the momentum fraction carried by the gluons is given by $x = \frac{M_{\mathrm{J}/\psi}}{\sqrt{s_{\mathrm{NN}}}} e^{\pm y}$, where $M_{\mathrm{J}/\psi}$ is the mass of the J/ψ, y is the rapidity, and $\sqrt{s_{\mathrm{NN}}}$ is the centre-of-mass rapidity per nucleon–nucleon collision. For rapidities $y \neq 0$ one thus has a two-fold ambiguity in the value of x. In the middle of the acceptance of the muon spectrometer $y = -3.25$. This corresponds to x-values of 2×10^{-3} and 5×10^{-5}. The largest contribution to the cross section comes from the higher value. Recent experimental data from ALICE, CMS, and LHCb [6–10] have found experimental evidence of gluon shadowing [11].

In previous analyses of exclusive vector meson photoproduction off protons at lower energies, using both real and virtual photons, the vector meson has generally been found to have transverse polarisation, as would be expected if the vector meson keeps the polarisation of the incoming photon (s-channel helicity conservation, SCHC) [12,13]. However, although early results from SLAC [14] and from the CERN SPS [15] with ρ^0 mesons produced from real photons are consistent with SCHC, a much more recent study of ρ^0, ω, and ϕ photoproduction from CLAS [16–18] reports violation of SCHC.

Exclusive photoproduction of vector mesons has also been studied at HERA in ep collisions. Both the H1 [19] and ZEUS [20] collaborations observed transverse polarisation in J/ψ photoproduction, thus favouring SCHC, in their photoproduction data. Note that at HERA, photoproduction, at very low photon Q^2 ($Q^2 \lesssim 0.05$ GeV^2), is distinguished from electroproduction at somewhat higher Q^2, even though both are photon–hadron interactions. Here Q^2 is the four-momentum transfer squared from the lepton to the nucleon vertex. In electroproduction the photon is more virtual, and can be partially longitudinally polarised. Accordingly, in J/ψ electroproduction the degree of longitudinal polarisation is seen to increase with Q^2 [21]. Photoproduction can also be studied in heavy-ion UPCs. Polarisation measurements have been re-

* E-mail address: alice-publications@cern.ch.

https://doi.org/10.1016/j.physletb.2025.139466
Received 10 May 2023; Received in revised form 13 March 2025; Accepted 9 April 2025
Available online 15 April 2025

ported by STAR for ρ^0 photoproduction [22] in collisions of gold nuclei at RHIC, and are consistent with SCHC.

For all previous vector meson photoproduction analyses at the LHC, when calculating the experimental acceptance, the vector meson has been assumed to have the same helicity as that of the initial photon that interacted with the target, i.e. SCHC. Since there is no fundamental physics principle that justifies SCHC, new polarisation and spin parameter measurements of photoproduced vector mesons at high energies could provide important insights.

In this Letter, the first polarisation measurement of coherent J/ψ photoproduction in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is presented. These events are defined by the reaction $\gamma + Pb \rightarrow J/\psi + Pb$, where the photon is emitted from one of the two colliding lead nuclei, and the J/ψ meson is reconstructed in the forward rapidity interval $-4.0 < y < -2.5$.

2. Detector description

The ALICE detector and its performance are described in [23,24]. Muons from J/ψ decays are measured in the single-arm muon spectrometer. For coherent J/ψ photoproduction, the hadron activity is required to be highly suppressed. For this reason, vetoes are applied using the V0 and ALICE Diffractive (AD) detectors. The muon spectrometer covers the pseudorapidity interval $-4.0 < \eta < -2.5$. It consists of a ten interaction length absorber followed by five tracking stations, the third of which is placed inside a dipole magnet with a 3 Tm integrated magnetic field, a 7.2 interaction length iron wall, and a trigger system located downstream of the iron wall. Each tracking station is made of two planes of cathode pad chambers, while the trigger system consists of four planes of resistive plate chambers arranged in two stations. Muon tracks are reconstructed using the tracking algorithm described in [25]. The V0 detector is composed of the V0A and V0C sub-detectors, consisting of 32 cells each and covering the pseudorapidity intervals $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively. The AD detector [26] is composed of the ADC and ADA sub-detectors with 4 cells each, located at -19.5 m and $+16.9$ m along the beam direction from the interaction point and covering the pseudorapidity intervals $-7.0 < \eta < -4.9$ and $4.7 < \eta < 6.3$, respectively [27]. The V0 and AD detectors are scintillator arrays with a time resolution better than 1 ns, allowing a distinction between beam–beam and beam–gas interactions.

3. Data selection and analysis

This analysis follows the same selections as those recently described in [28], which combines the ultra-peripheral Pb–Pb datasets at centre-of-mass energy per nucleon–nucleon collision $\sqrt{s_{NN}} = 5.02$ TeV collected in 2015 and 2018. The resulting dataset corresponds to an integrated luminosity of about 750 $\mu b^{-1} \pm 5\%$ (syst). The UPC event sample was recorded using a hardware trigger that requires at least two unlike-sign tracks in the muon spectrometer, and no activity in the V0A, ADA, and ADC detectors. The use of these forward detectors ensures the exclusivity condition. The single muon threshold for the transverse momentum p_T for the muon trigger system has been set to $p_T = 1$ GeV/c [29]. At the offline level further selections are applied. First, exactly two unlike-sign tracks are required in the muon spectrometer, where both tracks must be compatible with high-quality reconstructed muons as described in [28]. The tracks must fulfil the requirement on the radial coordinate of the track at the end of the absorber, and on the extrapolation to the nominal vertex [30]. Track segments in the tracking chambers are matched with corresponding segments in the trigger chambers. In addition, each muon and each dimuon are required to be in the pseudorapidity $-4.0 < \eta < -2.5$ and rapidity $-4.0 < y < -2.5$ intervals, respectively. In order to select events where coherent J/ψ production is strongly enhanced, the dimuon p_T is required to be less than 0.25 GeV/c, effectively rejecting most of the non–coherent J/ψ events as discussed in [28]. Finally, the V0A, ADA, and ADC vetoes are applied, and up to two hits are allowed in V0C, since the V0C acceptance overlaps with the that of the muon spectrometer. These offline level selections have wider time windows than those used for the trigger electronics, together with a more refined algorithm, allowing for a more precise rejection. Possible V0 and AD detector veto inefficiencies could originate from independent hadronic or electromagnetic pile-up interactions. The mean efficiency correction factor is 95%, accounting for V0A and AD veto inefficiencies, while the V0C veto is found to be fully efficient. Since the angular distributions studied in this analysis are not affected by the forward veto selections, only the muon-related efficiencies are considered.

The detector acceptance and efficiency ($A \times \epsilon$) for J/ψ and for ψ' are evaluated using a sample of events generated with STARlight 2.2.0 [31], which models the J/ψ as transversely polarised. The decay muons are then propagated using a model of the detector implemented in GEANT 3.21 [32] with realistic conditions. They are then reconstructed with the same algorithm as that used for the experimental data. This sample is also used to construct the response matrices which are needed for this measurement. Typical values of the $A \times \epsilon$ range from 0.41 for $\cos\theta \sim 0$, and down to 0.024 at the limit of the acceptance i.e. $\cos\theta \sim 0.56$ (see next section for definition of θ).

4. Angular distributions

The angular distribution (W) of the decay muons is described in terms of the three polarisation parameters λ_θ, λ_φ, and $\lambda_{\theta\varphi}$ using the following expression as a function of the polar angle θ and of the azimuthal angle φ, which respects parity conservation [33]:

$$W(\cos\theta, \varphi) \propto \frac{1}{3+\lambda_\theta} \left[1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi\right]. \tag{1}$$

It is also possible to study the data by using the following expressions

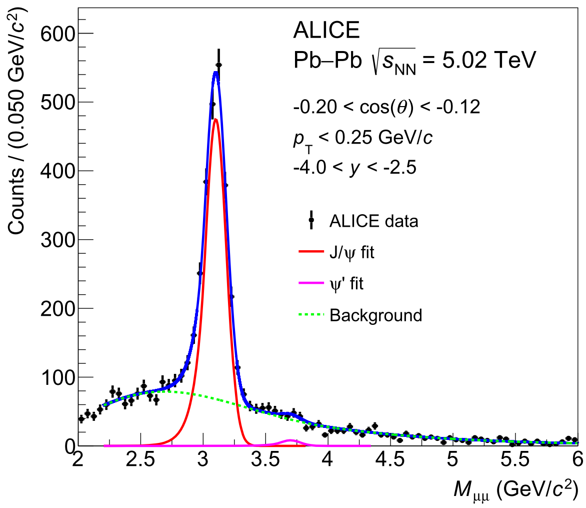
$$W(\cos\theta) \propto \frac{1}{3+\lambda_\theta} \left[1 + \lambda_\theta \cos^2\theta\right], \quad W(\varphi) \propto 1 + \frac{2\lambda_\varphi}{3+\lambda_\theta} \cos 2\varphi, \tag{2}$$

obtained by integrating Eq. (1) in the corresponding angular variable.

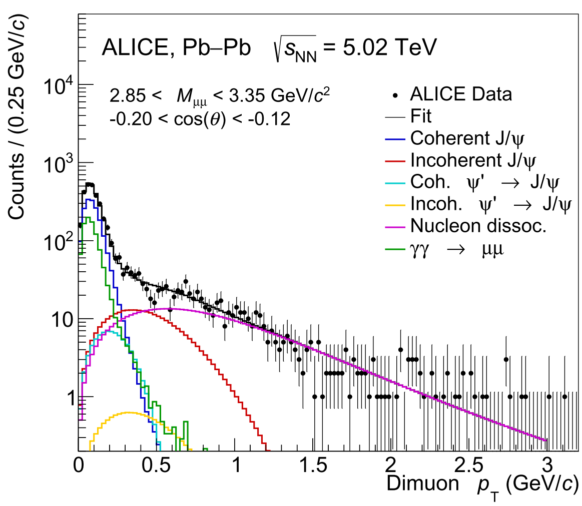
The polarisation parameters quantify the degree of polarisation. When all parameters are consistent with zero, an isotropic angular distribution is obtained. When $(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (1, 0, 0)$ the vector meson is transversely polarised, while $(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (-1, 0, 0)$ corresponds to a purely longitudinal polarisation.

The angular distribution of the decay muons is studied using the helicity frame. This frame has been used in recent studies of the polarisation of inclusive J/ψ production in pp and Pb–Pb collisions by the ALICE Collaboration [34–37], and by the PHENIX Collaboration in pp collisions [38]. In the helicity frame the z-axis coincides with the flight direction of the J/ψ in the Pb–Pb centre-of-mass frame. The y-axis is perpendicular to the plane formed by the collision axis and the direction of the J/ψ in the Pb–Pb centre-of-mass frame, while the x-axis is chosen so as to have a right-handed triplet [39]. The angles refer to the direction of the positive decay muon in this frame. Another commonly used definition of the axes is the Collins–Soper frame [33]. For J/ψ events at low p_T both frames are compatible, so results are only reported in terms of the helicity frame. The use of different reference frames has also been justified in terms of how the background could behave differently than the signal in the various frames. As discussed below, the background in this analysis is small which is expected for coherent J/ψ events.

To extract the J/ψ yield, the dimuon invariant mass distribution is fitted in the interval $2.2 < M_{\mu\mu} < 6.0$ GeV/c^2, requiring in addition that $p_T < 0.25$ GeV/c to enhance the contribution from coherent production. The study is performed in twenty-four bins of $\cos\theta$ over the interval $-1 < \cos\theta < 1$, and six bins in φ in the interval between 0 and 2π, to obtain yields in intervals of $\cos\theta$ and φ. As an example,



(a)



(b)

Fig. 1. A fit to the raw invariant mass (a) and p_T distributions for events in the $-0.20 < \cos\theta < -0.12$ range evaluated in the helicity frame. The bottom panel (b) shows the dimuon p_T around the J/ψ mass range. The displayed uncertainties are statistical.

Fig. 1(a) shows the invariant mass distribution of coherent J/ψ candidates in the interval $-0.20 < \cos\theta < -0.12$. We follow the procedure described in [28] for fitting the invariant mass distributions. The data are fitted to a background model (dimuon continuum) and to a signal model (J/ψ and ψ' resonances). For the background, the fitting function is given by a fourth-order polynomial multiplied by an exponential. The exponential component becomes important for $M_{\mu\mu} > 4.0$ GeV/c^2. The coefficients of the polynomial function are fixed to those obtained from Monte Carlo simulations using the STARlight [31] generator for the $\gamma\gamma \longrightarrow \mu^+\mu^-$ process. The exponential tail behaviour is expected for such an electromagnetic process. At low dimuon masses the detector acceptance decreases due to the trigger requirement, so the exponential part is not needed and a simple fourth-order polynomial is used. The J/ψ and ψ' signals are fitted with one-sided Crystal Ball functions [40]. The parameters for the Crystal Ball functions are fixed to those obtained from Monte Carlo templates. The mean and width of the J/ψ peak are free parameters in the fit. The mean of the ψ' peak is fixed to the world average value [41] and its width to that of the J/ψ multiplied by the ratio of the widths of the ψ' to the J/ψ, as measured from the analysis of reconstructed STARlight events. The ratio is approximately 1.09.

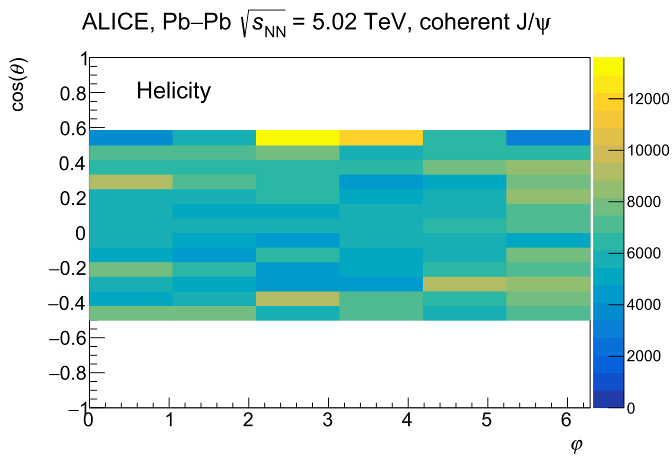


Fig. 2. Two-dimensional angular distribution of coherent J/ψ candidates in the helicity frame, after being unfolded in φ and corrected for $A \times \epsilon$ in $\cos\theta$.

The J/ψ yield extracted from the fit to the invariant mass distributions comprises five contributions, namely (*i*) coherent production, (*ii*) incoherent production, and (*iii*) feed-down J/ψ production from coherent ψ' production, incoherent ψ' production, and (*v*) incoherent J/ψ production with associated nucleon production. To extract the coherent J/ψ yield, the residual background has been estimated from fits to the dimuon p_T distribution. This is possible since the various processes have different momentum distributions of the produced J/ψ mesons. Incoherent J/ψ photoproduction accompanied by nucleon dissociation was also taken into account in order to describe the high p_T tail, using a template based on the H1 parametrization of the dissociative J/ψ photoproduction [42]. Following this approach, which has been described in a recent publication [28], the background contribution is found to be smaller than 4.6% for the integrated $\cos\theta$ and φ intervals used in this analysis. Note this fraction does not include the $\gamma\gamma \longrightarrow \mu^+\mu^-$ background which has been subtracted from fits to the invariant mass distribution, as described above. Since the residual background is small, and assuming that those J/ψ events have the same polarisation to that of coherent J/ψ events, their contributions are not subtracted from the sample. The J/ψ yield is estimated from the dimuon invariant mass distribution in a number of $(\cos(\theta), \varphi)$ cells assuming it all to be coherent. For illustration purposes, Fig. 1(b) shows the p_T distribution of candidates in the J/ψ invariant mass peak region ($2.85 < M_{\mu\mu} < 3.35$ GeV/c^2) and in the same $\cos(\theta)$ interval of Fig. 1(a).

To correct for detector effects, the data are unfolded and corrected for $A \times \epsilon$ in cells of $\cos\theta$ and φ, and in the 1D distributions, $A \times \epsilon$ corrections are applied to the data in $\cos\theta$. Since the STARLight Monte Carlo has been found to give a reasonable description of the data, in particular for coherent J/ψ production (low p_T events) at forward rapidity, we take this to be a natural starting point. The unfolding uses the Bayes' iterative method [43] as implemented in the RooUnfold framework [44]. The number of iterations in the unfolding procedure was set to fifteen. This number was found to be optimal at minimising the average uncertainty, following the prescription discussed in [45]. Since the generated $\cos\theta$ is recovered in the reconstructed $\cos\theta$ with a spread smaller than the bin width, bin migration effects are negligible and the data do not need unfolding in $\cos\theta$. Therefore, as in addition the sample size is small, the unfolding is performed only for φ, as described below. Fig. 2 shows the corrected J/ψ distribution in $\cos\theta$ and φ, where the φ distribution in addition has been unfolded. The unfolding procedure increases the uncertainties on the estimated number of J/ψs in each cell significantly. The first step is to fit the $\cos\theta$ distribution as a 1D distribution, treating the uncertainties in each bin as independent of those of the other bins. The $\cos\theta$ distribution is fitted using a χ^2 fitting method and the equivalent of Eq. (2) with the normalisation modified to take

Table 1
Summary of the systematic uncertainty contributions, presented as absolute values. The $\cos\theta$ range systematic uncertainty refers to the fitted range variation, the signal extraction to the choice of the description of the J/ψ, the unfolding systematic uncertainty is due to the choice of the number of iterations, the response matrix refers to the input distribution in generating the matrix, and the trigger systematic uncertainty is associated to the single muon p_T selection used for the trigger efficiency calculation.

Systematics	1D	2D		
	λ_θ	λ_θ	λ_φ	$\lambda_{\theta\varphi}$
$\cos\theta$ range	0.079	0.142	0.002	0.056
signal extraction	0.002	0.026	0.002	0.008
unfolding	0.0	0.019	0.004	0.004
response matrix	0.010	0.009	0.008	0.004
single muon p_T threshold	0.203	0.196	0.022	0.019
Total	0.218	0.244	0.023	0.060

into account the actual limits of integration, $-0.5 < \cos\theta < 0.583$. This gives $\lambda_\theta = 0.93 \pm 0.05(\text{stat}) \pm 0.22(\text{sys})$.

For the φ-related parameters λ_φ and $\lambda_{\theta\varphi}$, the 2D distribution is required, giving the best estimates of the content of each $(\cos\theta, \varphi)$ cell, where the φ distribution is unfolded independently in each $\cos\theta$ band. As the contents of the unfolded cells for a given $\cos\theta$ are correlated, an (input) covariance matrix was determined separately for each $\cos\theta$ band. The contents of each cell and their uncertainty, as determined before any unfolding from the fit to the invariant mass distribution, are used to generate 10000 samples with fluctuating contents according to a normal distribution. The contents of all bins are varied simultaneously, and the unfolding algorithm applied. The covariance matrix for the cell contents after unfolding is evaluated using $\text{cov}(x, y) = <xy> - <x><y>$. Finally, the whole (2D) angular distribution is fitted with Eq. (1), using a χ^2 method, the unfolded contents for the central values in each cell, and the set of convariance matrices. A free fit for all three parameters yields $\lambda_\theta = 0.82 \pm 0.44$, $\lambda_\varphi = 0.03 \pm 0.04$, and $\lambda_{\theta\varphi} = 0.10 \pm 0.09$. However, for the final fit the λ_θ value has been fixed to the value obtained from the 1D fit, allowing only λ_φ and $\lambda_{\theta\varphi}$ to vary. The χ^2/NDF for this final fit is 114.2/175.

Table 1 presents a summary of the various sources of systematic uncertainty on the measurement of the polarisation parameters for coherent J/ψ mesons. To study how the polarisation parameters vary as the acceptance changes when $\cos\theta$ increases, the polar angle distribution is fitted in the $\cos\theta$ ranges $[-0.5, 0.583]$ and $[-0.5, 0.5]$, as the analysis is carried out in a restricted $\cos\theta$ interval. The observed variation is taken as a systematic uncertainty. The uncertainty from the signal extraction is estimated by changing the J/ψ line shape from a single-sided Crystal Ball function to a double-sided one. The background fraction is thus adjusted accordingly in the fit. The uncertainty from the unfolding is assessed by varying the number of iterations by ± 1 with respect to the number chosen for the central value. The impact of the response matrix as a source of systematic uncertainty in the results is also investigated. Three different matrices corresponding to transverse polarisation, flat distribution and longitudinal polarisation have been used, and the differences in the fitted parameters were evaluated to determine the corresponding systematic uncertainty. Another source of systematic uncertainty is the trigger and tracking efficiency. This is studied by varying the offline p_T selection from 0.85 to 1.15 GeV/c for single muons, corresponding to a $\pm 5\%$ variation on the trigger efficiency. The choice of p_T selection and the $\cos\theta$ range are correlated. The larger the p_T, the smaller the allowed $\cos\theta$ range. Finally, the global systematic uncertainty on the polarisation parameters is obtained by adding the results of the various sources in quadrature.

5. Results and discussion

The projections of the angular distribution of the yield of coherently produced J/ψ in terms of $\cos\theta$ and φ are shown in Figs. 3(a) and 3(b), respectively. The numerical values of the polarisation parameters are given in Table 2. The numerical values of the polarisation parameters are given in Table 2, with the statistical uncertainty defined using $\Delta\chi^2 = 2.3$, since this is a two-dimensional distribution [46,47], and the systematic error calculated as described above. Note that the λ_θ result is taken from the 1D fit. The results are found to be consistent with $(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (1, 0, 0)$, i.e. transverse polarisation, and they satisfy the required positivity constraints [48].

Alternative formalisms exist for describing the polarisation parameters [13,48,49]. In order to provide a comparison with H1 [19] and ZEUS [20] results, the measured λ_θ and λ_φ values are converted to spin-density matrix elements $r^{\text{ik}}_{\lambda\lambda'}$ [13]. The conversion from lambda parameters to spin-density matrix elements $r^{\text{ik}}_{\lambda\lambda'}$ can be obtained from the following expressions [19]:

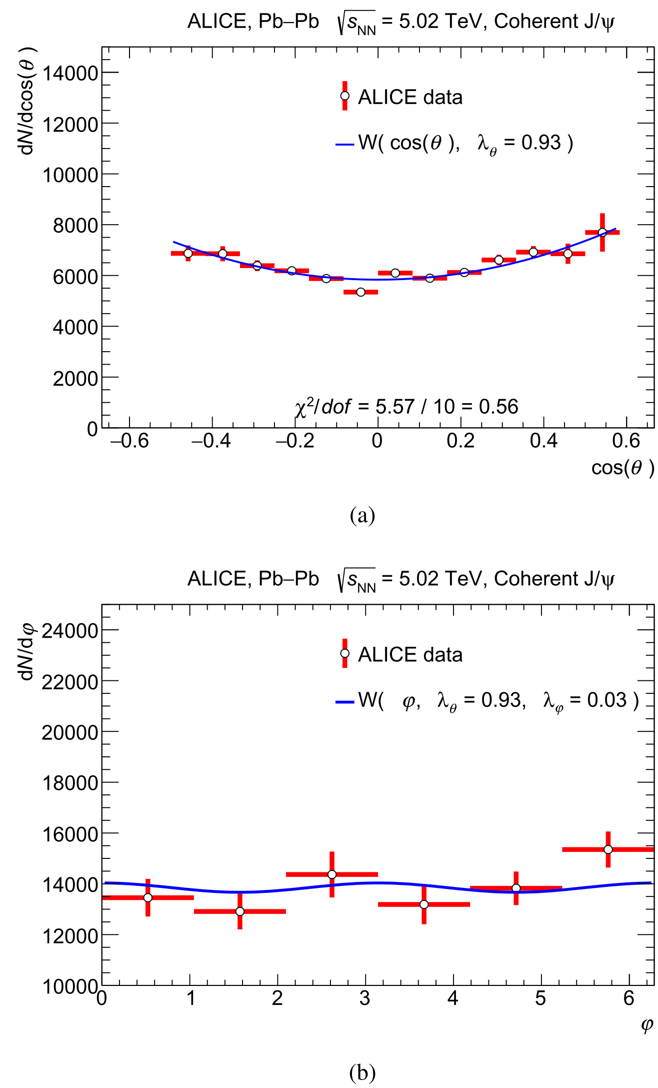


Fig. 3. Projections of the coherent J/ψ data points in (a) $\cos\theta$ and (b) φ, for events in the $-4 < y < -2.5$ rapidity interval. The curves are obtained by setting the lambda parameters in Eq. (2) to the results of the fit to the distribution given in Table 2. The uncertainties on the data points are statistical.

Table 2
Measured polarisation parameters for coherent J/ψ in the helicity frame. The central values are given with statistical and total systematic uncertainties.

λ_θ	λ_φ	$\lambda_{\theta\varphi}$
$0.93 \pm 0.05 \pm 0.22$	$0.03 \pm 0.04 \pm 0.02$	$0.10 \pm 0.09 \pm 0.06$

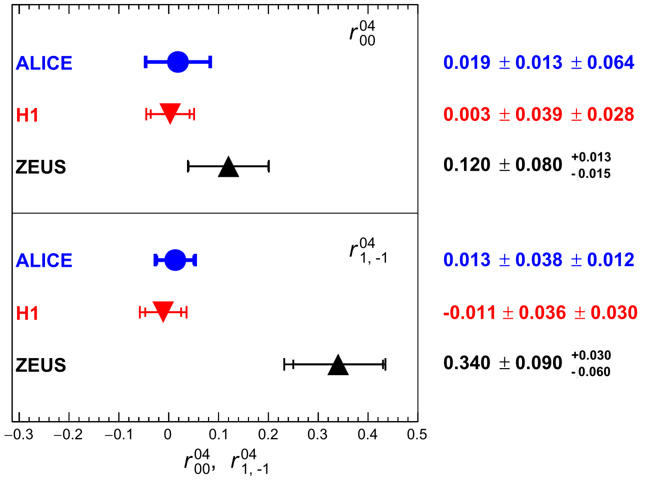


Fig. 4. ALICE results displayed in terms of spin density matrix elements, along with statistical and systematic uncertainties. A comparison with the available lowest Q^2 ranges of the results from the H1 and ZEUS collaborations is also provided. H1 results [19] correspond to $Q^2 \sim 0.05$ GeV^2 consistent with photoproduction, while the shown ZEUS measurement [20] is for $2 < Q^2 < 5$ GeV^2.

$$W(\cos\theta) \propto 1 + r^{04}_{00} + (1 - 3r^{04}_{00})\cos^2\theta$$
$$W(\varphi) \propto 1 + r^{04}_{1,-1}\cos 2\varphi\,. \tag{3}$$

By comparing Eq. (2) and Eq. (3), the spin-density matrix elements are expressed as:

$$r^{04}_{00} = \frac{1-\lambda_\theta}{3+\lambda_\theta}$$
$$r^{04}_{1,-1} = \frac{\lambda_\varphi}{2}(1 + r^{04}_{00})\,. \tag{4}$$

Fig. 4 shows the results of the comparison. In this analysis, the HERA measurements are given in the helicity frame. The ALICE result presented in Fig. 4 is compatible with the H1 measurement, which also uses a photoproduction sample ($Q^2 \lesssim 0.05$ GeV^2), and is lower than the ZEUS measurement, which uses a sample with $2 < Q^2 < 5$ GeV^2 [20]. This is the lowest Q^2 point in the ZEUS range, and it can be seen to be tending towards the photoproduction value found by H1, but is already in the electroproduction regime.

6. Summary

The first measurement of the polarisation of coherent J/ψ photoproduction in ultra-peripheral Pb–Pb collisions, using data at $\sqrt{s_{\rm NN}} = 5.02$ TeV, has been carried out by the ALICE Collaboration. The λ_θ, λ_φ, $\lambda_{\theta\varphi}$ parameters have been evaluated in the helicity reference frame in the rapidity interval $-4 < y < -2.5$. The λ_θ parameter has been found to be consistent with unity, and the other two parameters are found to be consistent with zero, indicating that coherently produced J/ψ mesons are transversely polarised as required for s-channel helicity conservation. The measured polarisation parameters are found to be compatible with those reported by the H1 Collaboration for J/ψ photoproduction in electron–proton interactions at lower energies, and evaluated in the helicity frame and using the spin density matrix formalism. This analysis represents the first experimental evidence that coherent J/ψ in ultra-peripheral Pb–Pb collisions at high energies is consistent with the photoproduction mechanism and the s-channel helicity conservation hypothesis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all Grid centres and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation (ANSL), State Committee of Science and World Federation of Scientists (WFS), Armenia; Austrian Academy of Sciences, Austrian Science Fund (FWF): [M 2467-N36] and Nationalstiftung für Forschung, Technologie und Entwicklung, Austria; Ministry of Communications and High Technologies, National Nuclear Research Center, Azerbaijan; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (Finep), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Universidade Federal do Rio Grande do Sul (UFRGS), Brazil; Bulgarian Ministry of Education and Science, within the National Roadmap for Research Infrastructures 2020-2027 (object CERN), Bulgaria; Ministry of Education of China (MOEC), Ministry of Science & Technology of China (MSTC) and National Natural Science Foundation of China (NSFC), China; Ministry of Science and Education and Croatian Science Foundation, Croatia; Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research | Natural Sciences, the Villum Fonden and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l'Énergie Atomique (CEA) and Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS), France; Bundesministerium für Bildung und Forschung (BMBF) and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany; General Secretariat for Research and Technology, Ministry of Education, Research and Religions, Greece; National Research, Development and Innovation Office, Hungary; Department of Atomic Energy, Government of India (DAE), Department of Science and Technology, Government of India (DST), University Grants Commission, Government of India (UGC) and Council of Scientific and Industrial Research (CSIR), India; National Research and Innovation Agency - BRIN, Indonesia; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Japan Society for the Promotion of Science (JSPS) KAKENHI, Japan; Consejo Nacional de Ciencia (CONACYT) y Tecnología, through Fondo de Cooperación Internacional en Ciencia y Tecnología (FONCICYT) and Dirección General de Asuntos del Personal Académico (DGAPA), Mexico; Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; The Research Council of Norway, Norway; Commission on Science and Technology for Sustainable Development in the South (COMSATS), Pakistan; Pontificia Universidad Católica del Perú, Peru; Ministry of Education and Science, National Science Centre and WUT ID-UB, Poland; Korea Institute of Science and Technology Information and National Research Foundation of Korea (NRF), Republic of Korea; Ministry of Education and Scientific Research, Institute of Atomic Physics, Ministry of Research and Innovation and Institute of Atomic Physics and Universitatea Nationala de Stiinta si Tehnologie Politehnica Bucuresti, Romania; Ministry of Education, Science, Research and Sport of the Slovak Republic, Slovakia; National Research Foundation of South Africa, South Africa; Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; Suranaree University of Technology (SUT), National Science and Technology Development Agency (NSTDA) and National Science, Research and Innovation Fund (NSRF via PMU-B B05F650021), Thailand; Turkish Energy, Nuclear and Mineral Research Agency (TENMAK), Turkey; National Academy of Sciences of Ukraine,

Ukraine; Science and Technology Facilities Council (STFC), United Kingdom; National Science Foundation of the United States of America (NSF) and United States Department of Energy, Office of Nuclear Physics (DOE NP), United States of America. In addition, individual groups or members have received support from: Czech Science Foundation (grant no. 23-07499S), Czech Republic; European Research Council, Strong 2020 - Horizon 2020, Marie Skłodowska Curie (grant nos. 950692, 824093, 896850), European Union; ICSC - Centro Nazionale di Ricerca in High Performance Computing, Big Data and Quantum Computing, European Union - NextGenerationEU; Academy of Finland (Center of Excellence in Quark Matter) (grant nos. 346327, 346328), Finland; Programa de Apoyos para la Superación del Personal Académico, UNAM, Mexico.

Data availability

Data will be made available on request.

References

[1] A.J. Baltz, The physics of ultraperipheral collisions at the LHC, Phys. Rep. 458 (2008) 1–171, arXiv:0706.3356 [nucl-ex].
[2] J.G. Contreras, J.D. Tapia Takaki, Ultra-peripheral heavy-ion collisions at the LHC, Int. J. Mod. Phys. A 30 (2015) 1542012.
[3] S. Klein, P. Steinberg, Photonuclear and two-photon interactions at high-energy nuclear colliders, Annu. Rev. Nucl. Part. Sci. 70 (2020) 323–354, arXiv:2005.01872 [nucl-ex].
[4] V. Guzey, E. Kryshen, M. Zhalov, Coherent photoproduction of vector mesons in ultraperipheral heavy ion collisions: update for run 2 at the CERN large hadron collider, Phys. Rev. C 93 (2016) 055206, arXiv:1602.01456 [nucl-th].
[5] D. Bendova, J. Cepila, J.G. Contreras, M. Matas, Photonuclear J/ψ production at the LHC: proton-based versus nuclear dipole scattering amplitudes, Phys. Lett. B 817 (2021) 136306, arXiv:2006.12980 [hep-ph].
[6] ALICE Collaboration, B. Abelev, et al., Coherent J/ψ photoproduction in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Lett. B 718 (2013) 1273–1283, arXiv:1209.3715 [nucl-ex].
[7] ALICE Collaboration, E. Abbas, et al., Charmonium and e^+e^- pair photoproduction at mid-rapidity in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Eur. Phys. J. C 73 (2013) 2617, arXiv:1305.1467 [nucl-ex].
[8] CMS Collaboration, V. Khachatryan, et al., Coherent J/ψ photoproduction in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV with the CMS experiment, Phys. Lett. B 772 (2017) 489–511, arXiv:1605.06966 [nucl-ex].
[9] CMS Collaboration, A. Tumasyan, et al., Probing small Bjorken-x nuclear gluonic structure via coherent J/ψ photoproduction in ultraperipheral pb-pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Phys. Rev. Lett. 131 (2023) 262301, https://doi.org/10.1103/PhysRevLett.131.262301, arXiv:2303.16984.
[10] LHCb Collaboration, R. Aaij, et al., Study of coherent J/ψ production in lead-lead collisions at $\sqrt{s}$ = 5 TeV, J. High Energy Phys. 07 (2022) 117, arXiv:2107.03223 [hep-ex].
[11] V. Guzey, E. Kryshen, M. Strikman, M. Zhalov, Evidence for nuclear gluon shadowing from the ALICE measurements of Pb–Pb ultraperipheral exclusive J/ψ production, Phys. Lett. B 726 (2013) 290–295, arXiv:1305.1724 [hep-ph].
[12] F.J. Gilman, J. Pumplin, A. Schwimmer, L. Stodolsky, Helicity conservation in diffraction scattering, Phys. Lett. B 31 (1970) 387–390.
[13] K. Schilling, G. Wolf, How to analyze vector meson production in inelastic lepton scattering, Nucl. Phys. B 61 (1973) 381–413.
[14] J. Ballam, et al., Vector meson production by polarized photons at 2.8 GeV, 4.7 GeV, and 9.3 GeV, Phys. Rev. D 7 (1973) 3150.
[15] OMEGA Photon Collaboration, R.J. Apsimon, et al., Comparison of photon and hadron induced production of ρ^0 mesons in the energy range of 65 GeV to 175 GeV, Z. Phys. C 53 (1992) 581–594.
[16] CLAS Collaboration, S.A. Morrow, et al., Exclusive ρ^0 electroproduction on the proton at CLAS, Eur. Phys. J. A 39 (2009) 5–31, arXiv:0807.3834 [hep-ex].
[17] CLAS Collaboration, B. Vernarsky, First measurements of the ρ^3 spin density matrix elements in $\gamma p \to p\omega$ using CLAS at JLAB, Int. J. Mod. Phys. Conf. Ser. 26 (2014) 1460063.
[18] CLAS Collaboration, B. Dey, et al., Data analysis techniques, differential cross sections, and spin density matrix elements for the reaction $\gamma p \to \phi p$, Phys. Rev. C 89 (2014) 055208, arXiv:1403.2110 [nucl-ex]; Addendum: Phys. Rev. C 90 (2014) 019901.
[19] H1 Collaboration, A. Aktas, et al., Elastic J/ψ production at HERA, Eur. Phys. J. C 46 (2006) 585–603, arXiv:hep-ex/0510016.
[20] ZEUS Collaboration, S. Chekanov, et al., Exclusive electroproduction of J/ψ mesons at HERA, Nucl. Phys. B 695 (2004) 3–37, arXiv:hep-ex/0404008.
[21] ZEUS Collaboration, J. Breitweg, et al., Exclusive electroproduction of ρ^0 and J/ψ mesons at HERA, Eur. Phys. J. C 6 (1999) 603–627, arXiv:hep-ex/9808020.
[22] STAR Collaboration, B.I. Abelev, et al., ρ^0 photoproduction in ultraperipheral relativistic heavy ion collisions at $\sqrt{s_{NN}}$ = 200 GeV, Phys. Rev. C 77 (2008) 034910, arXiv:0712.3320 [nucl-ex].
[23] ALICE Collaboration, K. Aamodt, et al., The ALICE experiment at the CERN LHC, J. Instrum. 3 (2008) S08002.
[24] ALICE Collaboration, B. Abelev, et al., Performance of the ALICE experiment at the CERN LHC, Int. J. Mod. Phys. A 29 (2014) 1430044, arXiv:1402.4476 [nucl-ex].
[25] ALICE Collaboration, K. Aamodt, et al., Rapidity and transverse momentum dependence of inclusive J/ψ production in pp collisions at $\sqrt{s}$ = 7 TeV, Phys. Lett. B 704 (2011) 442–455, arXiv:1105.0380 [hep-ex]; Erratum: Phys. Lett. B 718 (2012) 692.
[26] M. Broz, et al., Performance of ALICE AD modules in the CERN PS test beam, J. Instrum. 16 (2021) P01017, arXiv:2006.14982 [physics.ins-det].
[27] LHC Forward Physics Working Group Collaboration, K. Akiba, et al., LHC forward physics, J. Phys. G 43 (2016) 110201, arXiv:1611.05079 [hep-ph].
[28] ALICE Collaboration, S. Acharya, et al., Coherent J/ψ photoproduction at forward rapidity in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Phys. Lett. B 798 (2019) 134926, arXiv:1904.06272 [nucl-ex].
[29] ALICE Collaboration, F. Bossu, M. Gagliardi, M. Marchisone, Performance of the RPC-based ALICE muon trigger system at the LHC, PoS RPC2012 (2012) 059, arXiv:1211.1948 [physics.ins-det].
[30] ALICE Collaboration, B. Abelev, et al., Coherent J/ψ photoproduction in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Lett. B 718 (2013) 1273–1283, arXiv:1209.3715 [nucl-ex].
[31] S.R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, J. Butterworth, STARlight: a Monte Carlo simulation program for ultra-peripheral collisions of relativistic ions, Comput. Phys. Commun. 212 (2017) 258–268, arXiv:1607.03838 [hep-ph].
[32] R. Brun, F. Bruyant, F. Carminati, S. Giani, M. Maire, A. McPherson, G. Patrick, L. Urban, GEANT: Detector Description and Simulation Tool; Oct 1994, CERN Program Library, CERN, Geneva, 1993, http://cds.cern.ch/record/1082634, Long Writeup W5013.
[33] P. Faccioli, C. Lourenço, J. Seixas, H.K. Wöhri, Towards the experimental clarification of quarkonium polarization, Eur. Phys. J. C 69 (2010) 657–673, arXiv:1006.2738 [hep-ph].
[34] ALICE Collaboration, B. Abelev, et al., J/ψ polarization in pp collisions at $\sqrt{s}$ = 7 TeV, Phys. Rev. Lett. 108 (2012) 082001, arXiv:1111.1630 [hep-ex].
[35] ALICE Collaboration, S. Acharya, et al., Measurement of the inclusive J/ψ polarization at forward rapidity in pp collisions at $\sqrt{s}$ = 8 TeV, Eur. Phys. J. C 78 (2018) 562, arXiv:1805.04374 [hep-ex].
[36] ALICE Collaboration, S. Acharya, et al., First measurement of quarkonium polarization in nuclear collisions at the LHC, Phys. Lett. B 815 (2021) 136146, arXiv:2005.11128 [nucl-ex].
[37] ALICE Collaboration, S. Acharya, et al., Measurement of the J/ψ polarization with respect to the event plane in Pb–Pb collisions at the LHC, Phys. Rev. Lett. 131 (2023) 042303, arXiv:2204.10171 [nucl-ex].
[38] PHENIX Collaboration, U. Acharya, et al., Polarization and cross section of midrapidity J/ψ production in p+p collisions at $\sqrt{s}$ = 510 GeV, Phys. Rev. D 102 (2020) 072008, arXiv:2005.14273 [hep-ex].
[39] P. Faccioli, C. Lourenço, J. Seixas, A new approach to quarkonium polarization studies, Phys. Rev. D 81 (2010) 111502, arXiv:1005.2855 [hep-ph].
[40] J.E. Gaiser, Charmonium Spectroscopy from Radiative Decays of the J/ψ and ψ', PhD thesis, SLAC, 1982, http://inspirehep.net/record/183554/files/slac-r-255.pdf.
[41] Particle Data Group Collaboration, M. Tanabashi, et al., Review of particle physics, Phys. Rev. D 98 (2018) 030001.
[42] H1 Collaboration, C. Alexa, et al., Elastic and proton-dissociative photoproduction of J/ψ mesons at HERA, Eur. Phys. J. C 73 (2013) 2466, arXiv:1304.5162 [hep-ex].
[43] G. D'Agostini, A multidimensional unfolding method based on Bayes' theorem, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 362 (1995) 487–498.
[44] T. Adye, Unfolding algorithms and tests using RooUnfold, in: PHYSTAT 2011, CERN, Geneva, 2011, pp. 313–318, arXiv:1105.1160 [physics.data-an].
[45] S. Schmitt, Data unfolding methods in high energy physics, EPJ Web Conf. 137 (2017) 11008, arXiv:1611.01927 [physics.data-an].
[46] D. Drijard, W.T. Eadie, F.E. James, M. Roos, B. Sadoulet, Probability and Statistics Applied to High-Energy Physics, CERN Academic Training Lectures, vol. 39(7), 1968, p. 1, https://cds.cern.ch/record/318006, CERN, Geneva, 1968–1969.
[47] Particle Data Group Collaboration, S. Navas, et al., Review of particle physics, Phys. Rev. D 110 (2024) 030001, Section 40.4.2.3.
[48] J.C. Martens, J.P. Ralston, J.D. Tapia Takaki, Quantum tomography for collider physics: illustrations with lepton pair production, Eur. Phys. J. C 78 (2018) 5, arXiv:1707.01638 [hep-ph].
[49] M. Gavrilova, O. Teryaev, Rotation-invariant observables as density matrix invariants, Phys. Rev. D 99 (2019) 076013, arXiv:1901.04018 [hep-ph].

ALICE Collaboration

S. Acharya [126], D. Adamová [86], A. Adler [70], G. Aglieri Rinella [32], M. Agnello [29], N. Agrawal [51], Z. Ahammed [134], S. Ahmad [15], S.U. Ahn [71], I. Ahuja [37], A. Akindinov [140], M. Al-Turany [97], D. Aleksandrov [140], B. Alessandro [56], H.M. Alfanda [6], R. Alfaro Molina [67], B. Ali [15], A. Alici [25], N. Alizadehvandchali [115], A. Alkin [32], J. Alme [20], G. Alocco [52], T. Alt [64], I. Altsybeev [140], J.R. Alvarado [44], M.N. Anaam [6], C. Andrei [45], A. Andronic [125], V. Anguelov [94], F. Antinori [54], P. Antonioli [51], N. Apadula [74], L. Aphecetche [103], H. Appelshäuser [64], C. Arata [73], S. Arcelli [25], M. Aresti [52], R. Arnaldi [56], J.G.M.C.A. Arneiro [110], I.C. Arsene [19], M. Arslandok [137], A. Augustinus [32], R. Averbeck [97], M.D. Azmi [15], A. Badalà [53], J. Bae [104], Y.W. Baek [40], X. Bai [119], R. Bailhache [64], Y. Bailung [48], A. Balbino [29], A. Baldisseri [129], B. Balis [2], D. Banerjee [4], Z. Banoo [91], R. Barbera [26], F. Barile [31], L. Barioglio [95], M. Barlou [78], G.G. Barnaföldi [46], L.S. Barnby [85], V. Barret [126], L. Barreto [110], C. Bartels [118], K. Barth [32], E. Bartsch [64], N. Bastid [126], S. Basu [75], G. Batigne [103], D. Battistini [95], B. Batyunya [141], D. Bauri [47], J.L. Bazo Alba [101], I.G. Bearden [83], C. Beattie [137], P. Becht [97], D. Behera [48], I. Belikov [128], A.D.C. Bell Hechavarria [125], F. Bellini [25], R. Bellwied [115], S. Belokurova [140], V. Belyaev [140], G. Bencedi [46], S. Beole [24], A. Bercuci [45], Y. Berdnikov [140], A. Berdnikova [94], L. Bergmann [94], M.G. Besoiu [63], L. Betev [32], P.P. Bhaduri [134], A. Bhasin [91], M.A. Bhat [4], B. Bhattacharjee [41], L. Bianchi [24], N. Bianchi [49], J. Bielčík [35], J. Bielčíková [86], J. Biernat [107], A.P. Bigot [128], A. Bilandzic [95], G. Biro [46], S. Biswas [4], N. Bize [103], J.T. Blair [108], D. Blau [140], M.B. Blidaru [97], N. Bluhme [38], C. Blume [64], G. Boca [21,55], F. Bock [87], T. Bodova [20], A. Bogdanov [140], S. Boi [22], J. Bok [58], L. Boldizsár [46], M. Bombara [37], P.M. Bond [32], G. Bonomi [133,55], H. Borel [129], A. Borissov [140], A.G. Borquez Carcamo [94], H. Bossi [137], E. Botta [24], Y.E.M. Bouziani [64], L. Bratrud [64], P. Braun-Munzinger [97], M. Bregant [110], M. Broz [35], G.E. Bruno [96,31], M.D. Buckland [23], D. Budnikov [140], H. Buesching [64], S. Bufalino [29], P. Buhler [102], Z. Buthelezi [68,122], A. Bylinkin [20], S.A. Bysiak [107], M. Cai [6], H. Caines [137], A. Caliva [97], E. Calvo Villar [101], J.M.M. Camacho [109], P. Camerini [23], F.D.M. Canedo [110], S.L. Cantway [137], M. Carabas [113], A.A. Carballo [32], F. Carnesecchi [32], R. Caron [127], L.A.D. Carvalho [110], J. Castillo Castellanos [129], F. Catalano [24], C. Ceballos Sanchez [141], I. Chakaberia [74], P. Chakraborty [47], S. Chandra [134], S. Chapeland [32], M. Chartier [118], S. Chattopadhyay [134], S. Chattopadhyay [99], T. Cheng [97,6], C. Cheshkov [127], B. Cheynis [127], V. Chibante Barroso [32], D.D. Chinellato [111], E.S. Chizzali [95,II], J. Cho [58], S. Cho [58], P. Chochula [32], P. Christakoglou [84], C.H. Christensen [83], P. Christiansen [75], T. Chujo [124], M. Ciacco [29], C. Cicalo [52], F. Cindolo [51], M.R. Ciupek [97], G. Clai [51,III], F. Colamaria [50], J.S. Colburn [100], D. Colella [96,31], M. Colocci [25], M. Concas [56], G. Conesa Balbastre [73], Z. Conesa del Valle [130], G. Contin [23], J.G. Contreras [35], M.L. Coquet [129], T.M. Cormier [87,I], P. Cortese [132,56], M.R. Cosentino [112], F. Costa [32], S. Costanza [21,55], C. Cot [130], J. Crkovská [94], P. Crochet [126], R. Cruz-Torres [74], P. Cui [6], A. Dainese [54], M.C. Danisch [94], A. Danu [63], P. Das [80], P. Das [4], S. Das [4], A.R. Dash [125], S. Dash [47], A. De Caro [28], G. de Cataldo [50], J. de Cuveland [38], A. De Falco [22], D. De Gruttola [28], N. De Marco [56], C. De Martin [23], S. De Pasquale [28], R. Deb [133], S. Deb [48], R.J. Debski [2], K.R. Deja [135], R. Del Grande [95], L. Dello Stritto [28], W. Deng [6], P. Dhankher [18], D. Di Bari [31], A. Di Mauro [32], R.A. Diaz [141,7], T. Dietel [114], Y. Ding [6], R. Divià [32], D.U. Dixit [18], Ø. Djuvsland [20], U. Dmitrieva [140], A. Dobrin [63], B. Dönigus [64], J.M. Dubinski [135], A. Dubla [97], S. Dudi [90], P. Dupieux [126], M. Durkac [106], N. Dzalaiova [12], T.M. Eder [125], R.J. Ehlers [74], V.N. Eikeland [20], F. Eisenhut [64], D. Elia [50], B. Erazmus [103], F. Ercolessi [25], F. Erhardt [89], M.R. Ersdal [20], B. Espagnon [130], G. Eulisse [32], D. Evans [100], S. Evdokimov [140], L. Fabbietti [95], M. Faggin [27], J. Faivre [73], F. Fan [6], W. Fan [74], A. Fantoni [49], M. Fasel [87], P. Fecchio [29], A. Feliciello [56], G. Feofilov [140], A. Fernández Téllez [44], L. Ferrandi [110], M.B. Ferrer [32], A. Ferrero [129], C. Ferrero [56,IV], A. Ferretti [24], V.J.G. Feuillard [94], V. Filova [35], D. Finogeev [140], F.M. Fionda [52], F. Flor [115], A.N. Flores [108], S. Foertsch [68], I. Fokin [94], S. Fokin [140], E. Fragiacomo [57], E. Frajna [46], U. Fuchs [32], N. Funicello [28], C. Furget [73], A. Furs [140], T. Fusayasu [98], J.J. Gaardhøje [83], M. Gagliardi [24], A.M. Gago [101], C.D. Galvan [109], D.R. Gangadharan [115], P. Ganoti [78], C. Garabatos [97], T. García Chávez [44], E. Garcia-Solis [9], C. Gargiulo [32], K. Garner [125], P. Gasik [97], A. Gautam [117], M.B. Gay Ducati [66], M. Germain [103], A. Ghimouz [124], C. Ghosh [134], M. Giacalone [51,25], P. Giubellino [97,56], P. Giubilato [27], A.M.C. Glaenzer [129], P. Glässel [94], E. Glimos [121], D.J.Q. Goh [76], V. Gonzalez [136], M. Gorgon [2], S. Gotovac [33], V. Grabski [67], L.K. Graczykowski [135], E. Grecka [86], A. Grelli [59], C. Grigoras [32], V. Grigoriev [140], S. Grigoryan [141,1], F. Grosa [32], J.F. Grosse-Oetringhaus [32], R. Grosso [97], D. Grund [35], G.G. Guardiano [111], R. Guernane [73], M. Guilbaud [103], K. Gulbrandsen [83], T. Gündem [64], T. Gunji [123], W. Guo [6], A. Gupta [91], R. Gupta [91], R. Gupta [48], K. Gwizdziel [135], L. Gyulai [46], M.K. Habib [97], C. Hadjidakis [130], F.U. Haider [91], H. Hamagaki [76], A. Hamdi [74], M. Hamid [6], Y. Han [138], R. Hannigan [108], M.R. Haque [135], J.W. Harris [137], A. Harton [9], H. Hassan [87], D. Hatzifotiadou [51], P. Hauer [42], L.B. Havener [137], S.T. Heckel [95], E. Hellbär [97], H. Helstrup [34], M. Hemmer [64], T. Herman [35], G. Herrera Corral [8], F. Herrmann [125], S. Herrmann [127], K.F. Hetland [34], B. Heybeck [64], H. Hillemanns [32], B. Hippolyte [128], F.W. Hoffmann [70], B. Hofman [59], B. Hohlweger [84], G.H. Hong [138], M. Horst [95], A. Horzyk [2], Y. Hou [6], P. Hristov [32], C. Hughes [121], P. Huhn [64], L.M. Huhta [116], T.J. Humanic [88], A. Hutson [115], D. Hutter [38], J.P. Iddon [118], R. Ilkaev [140], H. Ilyas [13], M. Inaba [124], G.M. Innocenti [32], M. Ippolitov [140], A. Isakov [86], T. Isidori [117], M.S. Islam [99], M. Ivanov [97], M. Ivanov [12], V. Ivanov [140], M. Jablonski [2], B. Jacak [74], N. Jacazio [32], P.M. Jacobs [74], S. Jadlovska [106], J. Jadlovsky [106], S. Jaelani [82], L. Jaffe [38], C. Jahnke [111], M.J. Jakubowska [135], M.A. Janik [135], T. Janson [70], M. Jercic [89], S. Jia [10], A.A.P. Jimenez [65], F. Jonas [87,125], J.M. Jowett [32,97], J. Jung [64], M. Jung [64], A. Junique [32], A. Jusko [100], J. Kaewjai [105], P. Kalinak [60], A.S. Kalteyer [97], A. Kalweit [32], V. Kaplin [140], A. Karasu Uysal [72,V], D. Karatovic [89], O. Karavichev [140], T. Karavicheva [140], P. Karczmarczyk [135], E. Karpechev [140], M.J. Karwowska [32,135], U. Kebschull [70], R. Keidel [139], D.L.D. Keijdener [59], M. Keil [32], B. Ketzer [42], S.S. Khade [48], A.M. Khan [6], S. Khan [15], A. Khanzadeev [140], Y. Kharlov [140], A. Khatun [117,15], A. Khuntia [107], M.B. Kidson [114], B. Kileng [34], B. Kim [104], C. Kim [16], D.J. Kim [116], E.J. Kim [69], J. Kim [138], J.S. Kim [40], J. Kim [69], M. Kim [18,94], S. Kim [17], T. Kim [138], K. Kimura [92], S. Kirsch [64], I. Kisel [38], S. Kiselev [140], A. Kisiel [135], J.P. Kitowski [2], J.L. Klay [5], J. Klein [32], S. Klein [74], C. Klein-Bösing [125], M. Kleiner [64], T. Klemenz [95], A. Kluge [32], A.G. Knospe [115], C. Kobdaj [105], T. Kollegger [97], A. Kondratyev [141], N. Kondratyeva [140], E. Kondratyuk [140], J. Konig [64], S.A. Konigstorfer [95], P.J. Konopka [32], G. Kornakov [135], M. Korwieser [95], S.D. Koryciak [2], A. Kotliarov [86], V. Kovalenko [140], M. Kowalski [107], V. Kozhuharov [36], I. Králik [60], A. Kravčáková [37], L. Krcal [32,38], L. Kreis [97], M. Krivda [100,60], F. Krizek [86], K. Krizkova Gajdosova [32], M. Kroesen [94], M. Krüger [64], D.M. Krupova [35], E. Kryshen [140], V. Kučera [32], C. Kuhn [128], P.G. Kuijer [84], T. Kumaoka [124], D. Kumar [134], L. Kumar [90], N. Kumar [90], S. Kumar [31], S. Kundu [32], P. Kurashvili [79], A. Kurepin [140], A.B. Kurepin [140], A. Kuryakin [140], S. Kushpil [86], J. Kvapil [100], M.J. Kweon [58], J.Y. Kwon [58],

Y. Kwon [138], S.L. La Pointe [38], P. La Rocca [26], A. Lakrathok [105], M. Lamanna [32], R. Langoy [120], P. Larionov [32], E. Laudi [32], L. Lautner [32,95], R. Lavicka [102], T. Lazareva [140], R. Lea [133,55], H. Lee [104], G. Legras [125], J. Lehrbach [38], T.M. Lelek [2], R.C. Lemmon [85], I. León Monzón [109], M.M. Lesch [95], E.D. Lesser [18], P. Lévai [46], X. Li [10], X.L. Li [6], J. Lien [120], R. Lietava [100], I. Likmeta [115], B. Lim [24], S.H. Lim [16], V. Lindenstruth [38], A. Lindner [45], C. Lippmann [97], A. Liu [18], D.H. Liu [6], J. Liu [118], I.M. Lofnes [20], C. Loizides [87], S. Lokos [107], J. Lömker [59], P. Loncar [33], J.A. Lopez [94], X. Lopez [126], E. López Torres [7], P. Lu [97,119], J.R. Luhder [125], M. Lunardon [27], G. Luparello [57], Y.G. Ma [39], A. Maevskaya [140], M. Mager [32], A. Maire [128], M.V. Makariev [36], M. Malaev [140], G. Malfattore [25], N.M. Malik [91], Q.W. Malik [19], S.K. Malik [91], L. Malinina [141,I,VIII], D. Mal'Kevich [140], D. Mallick [80], N. Mallick [48], G. Mandaglio [30,53], S.K. Mandal [79], V. Manko [140], F. Manso [126], V. Manzari [50], Y. Mao [6], G.V. Margagliotti [23], A. Margotti [51], A. Marín [97], C. Markert [108], P. Martinengo [32], J.L. Martinez [115], M.I. Martínez [44], G. Martínez García [103], S. Masciocchi [97], M. Masera [24], A. Masoni [52], L. Massacrier [130], A. Mastroserio [131,50], O. Matonoha [75], P.F.T. Matuoka [110], A. Matyja [107], C. Mayer [107], A.L. Mazuecos [32], F. Mazzaschi [24], M. Mazzilli [32], J.E. Mdhluli [122], A.F. Mechler [64], Y. Melikyan [43,140], A. Menchaca-Rocha [67], E. Meninno [102], A.S. Menon [115], M. Meres [12], S. Mhlanga [114,68], Y. Miake [124], L. Micheletti [56], L.C. Migliorin [127], D.L. Mihaylov [95], K. Mikhaylov [141,140], A.N. Mishra [46], D. Miśkowiec [97], A. Modak [4], A.P. Mohanty [59], B. Mohanty [80], M. Mohisin Khan [15,VI], M.A. Molander [43], Z. Moravcova [83], C. Mordasini [95], D.A. Moreira De Godoy [125], I. Morozov [140], A. Morsch [32], T. Mrnjavac [32], V. Muccifora [49], S. Muhuri [134], J.D. Mulligan [74], A. Mulliri [22], M.G. Munhoz [110], R.H. Munzer [64], H. Murakami [123], S. Murray [114], L. Musa [32], J. Musinsky [60], J.W. Myrcha [135], B. Naik [122], A.I. Nambrath [18], B.K. Nandi [47], R. Nania [51], E. Nappi [50], A.F. Nassirpour [17,75], A. Nath [94], C. Nattrass [121], M.N. Naydenov [36], A. Neagu [19], A. Negru [113], L. Nellen [65], S.V. Nesbo [34], G. Neskovic [38], D. Nesterov [140], B.S. Nielsen [83], E.G. Nielsen [83], S. Nikolaev [140], S. Nikulin [140], V. Nikulin [140], F. Noferini [51], S. Noh [11], P. Nomokonov [141], J. Norman [118], N. Novitzky [124], P. Nowakowski [135], A. Nyanin [140], J. Nystrand [20], M. Ogino [76], A. Ohlson [75], V.A. Okorokov [140], J. Oleniacz [135], A.C. Oliveira Da Silva [121], M.H. Oliver [137], A. Onnerstad [116], C. Oppedisano [56], A. Ortiz Velasquez [65], J. Otwinowski [107], M. Oya [92], K. Oyama [76], Y. Pachmayer [94], S. Padhan [47], D. Pagano [133,55], G. Paić [65], S. Paisano-Guzmán [44], A. Palasciano [50], S. Panebianco [129], H. Park [124], H. Park [104], J. Park [58], J.E. Parkkila [32], R.N. Patra [91], B. Paul [22], H. Pei [6], T. Peitzmann [59], X. Peng [6], M. Pennisi [24], L.G. Pereira [66], D. Peresunko [140], G.M. Perez [7], S. Perrin [129], Y. Pestov [140], V. Petráček [35], V. Petrov [140], M. Petrovici [45], R.P. Pezzi [103,66], S. Piano [57], M. Pikna [12], P. Pillot [103], O. Pinazza [51,32], L. Pinsky [115], C. Pinto [95], S. Pisano [49], M. Płoskoń [74], M. Planinic [89], F. Pliquett [64], M.G. Poghosyan [87], B. Polichtchouk [140], S. Politano [29], N. Poljak [89], A. Pop [45], S. Porteboeuf-Houssais [126], V. Pozdniakov [141], I.Y. Pozos [44], K.K. Pradhan [48], S.K. Prasad [4], S. Prasad [48], R. Preghenella [51], F. Prino [56], C.A. Pruneau [136], I. Pshenichnov [140], M. Puccio [32], S. Pucillo [24], Z. Pugelova [106], S. Qiu [84], L. Quaglia [24], R.E. Quishpe [115], S. Ragoni [14], A. Rakotozafindrabe [129], L. Ramello [132,56], F. Rami [128], T.A. Rancien [73], M. Rasa [26], S.S. Räsänen [43], R. Rath [51], M.P. Rauch [20], I. Ravasenga [84], K.F. Read [87,121], C. Reckziegel [112], A.R. Redelbach [38], K. Redlich [79,VII], C.A. Reetz [97], H.D. Regules-Medel [44], A. Rehman [20], F. Reidt [32], H.A. Reme-Ness [34], Z. Rescakova [37], K. Reygers [94], A. Riabov [140], V. Riabov [140], R. Ricci [28], M. Richter [19], A.A. Riedel [95], W. Riegler [32], C. Ristea [63], M. Rodríguez Cahuantzi [44], S.A. Rodríguez Ramírez [44],

K. Røed [19], R. Rogalev [140], E. Rogochaya [141], T.S. Rogoschinski [64], D. Rohr [32], D. Röhrich [20], P.F. Rojas [44], S. Rojas Torres [35], P.S. Rokita [135], G. Romanenko [141], F. Ronchetti [49], A. Rosano [30,53], E.D. Rosas [65], K. Roslon [135], A. Rossi [54], A. Roy [48], S. Roy [47], N. Rubini [25], D. Ruggiano [135], R. Rui [23], B. Rumyantsev [141], P.G. Russek [2], R. Russo [84], A. Rustamov [81], E. Ryabinkin [140], Y. Ryabov [140], A. Rybicki [107], H. Rytkonen [116], W. Rzesa [135], O.A.M. Saarimaki [43], R. Sadek [103], S. Sadhu [31], S. Sadovsky [140], J. Saetre [20], K. Šafařík [35], S.K. Saha [4], S. Saha [80], B. Sahoo [47], B. Sahoo [48], R. Sahoo [48], S. Sahoo [61], D. Sahu [48], P.K. Sahu [61], J. Saini [134], K. Sajdakova [37], S. Sakai [124], M.P. Salvan [97], S. Sambyal [91], I. Sanna [32,95], T.B. Saramela [110], D. Sarkar [136], N. Sarkar [134], P. Sarma [41], V. Sarritzu [22], V.M. Sarti [95], M.H.P. Sas [137], J. Schambach [87], H.S. Scheid [64], C. Schiaua [45], R. Schicker [94], A. Schmah [94], C. Schmidt [97], H.R. Schmidt [93], M.O. Schmidt [32], M. Schmidt [93], N.V. Schmidt [87], A.R. Schmier [121], R. Schotter [128], A. Schröter [38], J. Schukraft [32], K. Schwarz [97], K. Schweda [97], G. Scioli [25], E. Scomparin [56], J.E. Seger [14], Y. Sekiguchi [123], D. Sekihata [123], I. Selyuzhenkov [97,140], S. Senyukov [128], J.J. Seo [58], D. Serebryakov [140], L. Šerkšnytė [95], A. Sevcenco [63], T.J. Shaba [68], A. Shabetai [103], R. Shahoyan [32], A. Shangaraev [140], A. Sharma [90], B. Sharma [91], D. Sharma [47], H. Sharma [107], M. Sharma [91], S. Sharma [76], S. Sharma [91], U. Sharma [91], A. Shatat [130], O. Sheibani [115], K. Shigaki [92], M. Shimomura [77], J. Shin [11], S. Shirinkin [140], Q. Shou [39], Y. Sibiriak [140], S. Siddhanta [52], T. Siemiarczuk [79], T.F. Silva [110], D. Silvermyr [75], T. Simantathammakul [105], R. Simeonov [36], B. Singh [91], B. Singh [95], R. Singh [80], R. Singh [91], R. Singh [48], S. Singh [15], V.K. Singh [134], V. Singhal [134], T. Sinha [99], B. Sitar [12], M. Sitta [132,56], T.B. Skaali [19], G. Skorodumovs [94], M. Slupecki [43], N. Smirnov [137], R.J.M. Snellings [59], E.H. Solheim [19], J. Song [115], A. Songmoolnak [105], F. Soramel [27], A.B. Soto-hernandez [88], R. Spijkers [84], I. Sputowska [107], J. Staa [75], J. Stachel [94], I. Stan [63], P.J. Steffanic [121], S.F. Stiefelmaier [94], D. Stocco [103], I. Storehaug [19], P. Stratmann [125], S. Strazzi [25], C.P. Stylianidis [84], A.A.P. Suaide [110], C. Suire [130], M. Sukhanov [140], M. Suljic [32], R. Sultanov [140], V. Sumberia [91], S. Sumowidagdo [82], S. Swain [61], I. Szarka [12], M. Szymkowski [135], S.F. Taghavi [95], G. Taillepied [97], J. Takahashi [111], G.J. Tambave [20], S. Tang [126,6], Z. Tang [119], J.D. Tapia Takaki [117], N. Tapus [113], L.A. Tarasovicova [125], M.G. Tarzila [45], G.F. Tassielli [31], A. Tauro [32], G. Tejeda Muñoz [44], A. Telesca [32], L. Terlizzi [24], C. Terrevoli [115], S. Thakur [4], D. Thomas [108], A. Tikhonov [140], A.R. Timmins [115], M. Tkacik [106], T. Tkacik [106], A. Toia [64], R. Tokumoto [92], N. Topilskaya [140], M. Toppi [49], F. Torales-Acosta [18], T. Tork [130], A.G. Torres Ramos [31], A. Trifiró [30,53], A.S. Triolo [32,30,53], S. Tripathy [51], T. Tripathy [47], S. Trogolo [32], V. Trubnikov [3], W.H. Trzaska [116], T.P. Trzcinski [135], A. Tumkin [140], R. Turrisi [54], T.S. Tveter [19], K. Ullaland [20], B. Ulukutlu [95], A. Uras [127], M. Urioni [55,133], G.L. Usai [22], M. Vala [37], N. Valle [21], L.V.R. van Doremalen [59], C. Van Hulse [130], M. van Leeuwen [84], C.A. van Veen [94], R.J.G. van Weelden [84], P. Vande Vyvre [32], D. Varga [46], Z. Varga [46], M. Vasileiou [78], A. Vasiliev [140], O. Vázquez Doce [49], O. Vazquez Rueda [115], V. Vechernin [140], E. Vercellin [24], S. Vergara Limón [44], L. Vermunt [97], R. Vértesi [46], M. Verweij [59], L. Vickovic [33], Z. Vilakazi [122], O. Villalobos Baillie [100], A. Villani [23], G. Vino [50], A. Vinogradov [140], T. Virgili [28], M.M.O. Virta [116], V. Vislavicius [75], A. Vodopyanov [141], B. Volkel [32], M.A. Völkl [94], K. Voloshin [140], S.A. Voloshin [136], G. Volpe [31], B. von Haller [32], I. Vorobyev [95], N. Vozniuk [140], J. Vrláková [37], C. Wang [39], D. Wang [39], Y. Wang [39], A. Wegrzynek [32], F.T. Weiglhofer [38], S.C. Wenzel [32], J.P. Wessels [125], J. Wiechula [64], J. Wikne [19], G. Wilk [79], J. Wilkinson [97], G.A. Willems [125], B. Windelband [94], M. Winn [129], J.R. Wright [108], W. Wu [39], Y. Wu [119], R. Xu [6], A. Yadav [42], A.K. Yadav [134], S. Yalcin [72], Y. Yamaguchi [92], S. Yang [20], S. Yano [92], Z. Yin [6], I.-K. Yoo [16], J.H. Yoon [58], S. Yuan [20], A. Yuncu [94], V. Zaccolo [23], C. Zampolli [32], F. Zanone [94], N. Zardoshti [32], A. Zarochentsev [140], P. Závada [62], N. Zaviyalov [140], M. Zhalov [140], B. Zhang [6], L. Zhang [39], M. Zhang [6], S. Zhang [39], X. Zhang [6], Y. Zhang [119], Z. Zhang [6], M. Zhao [10], V. Zherebchevskii [140], Y. Zhi [10], D. Zhou [6], Y. Zhou [83], J. Zhu [97,6], Y. Zhu [6], S.C. Zugravel [56], N. Zurlo [133,55]

[1] A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
[2] AGH University of Krakow, Cracow, Poland
[3] Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine
[4] Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
[5] California Polytechnic State University, San Luis Obispo, CA, United States
[6] Central China Normal University, Wuhan, China
[7] Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
[8] Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
[9] Chicago State University, Chicago, IL, United States
[10] China Institute of Atomic Energy, Beijing, China
[11] Chungbuk National University, Cheongju, Republic of Korea
[12] Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovak Republic
[13] COMSATS University Islamabad, Islamabad, Pakistan
[14] Creighton University, Omaha, NE, United States
[15] Department of Physics, Aligarh Muslim University, Aligarh, India
[16] Department of Physics, Pusan National University, Pusan, Republic of Korea
[17] Department of Physics, Sejong University, Seoul, Republic of Korea
[18] Department of Physics, University of California, Berkeley, CA, United States
[19] Department of Physics, University of Oslo, Oslo, Norway
[20] Department of Physics and Technology, University of Bergen, Bergen, Norway
[21] Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[22] Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
[23] Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
[24] Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
[25] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy
[26] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
[27] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
[28] Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
[29] Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
[30] Dipartimento di Scienze MIFT, Università di Messina, Messina, Italy
[31] Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
[32] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[33] Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia
[34] Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway
[35] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
[36] Faculty of Physics, Sofia University, Sofia, Bulgaria
[37] Faculty of Science, P.J. Šafárik University, Košice, Slovak Republic
[38] Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[39] Fudan University, Shanghai, China
[40] Gangneung-Wonju National University, Gangneung, Republic of Korea
[41] Gauhati University, Department of Physics, Guwahati, India
[42] Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
[43] Helsinki Institute of Physics (HIP), Helsinki, Finland
[44] High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico
[45] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[46] HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[47] Indian Institute of Technology Bombay (IIT), Mumbai, India
[48] Indian Institute of Technology Indore, Indore, India
[49] INFN, Laboratori Nazionali di Frascati, Frascati, Italy
[50] INFN, Sezione di Bari, Bari, Italy
[51] INFN, Sezione di Bologna, Bologna, Italy
[52] INFN, Sezione di Cagliari, Cagliari, Italy
[53] INFN, Sezione di Catania, Catania, Italy
[54] INFN, Sezione di Padova, Padova, Italy
[55] INFN, Sezione di Pavia, Pavia, Italy
[56] INFN, Sezione di Torino, Turin, Italy
[57] INFN, Sezione di Trieste, Trieste, Italy
[58] Inha University, Incheon, Republic of Korea
[59] Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University/Nikhef, Utrecht, Netherlands
[60] Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovak Republic
[61] Institute of Physics, Homi Bhabha National Institute, Bhubaneswar, India
[62] Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[63] Institute of Space Science (ISS), Bucharest, Romania
[64] Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[65] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
[66] Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
[67] Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
[68] iThemba LABS, National Research Foundation, Somerset West, South Africa
[69] Jeonbuk National University, Jeonju, Republic of Korea
[70] Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik, Frankfurt, Germany

[71] Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
[72] KTO Karatay University, Konya, Turkey
[73] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
[74] Lawrence Berkeley National Laboratory, Berkeley, CA, United States
[75] Lund University Department of Physics, Division of Particle Physics, Lund, Sweden
[76] Nagasaki Institute of Applied Science, Nagasaki, Japan
[77] Nara Women's University (NWU), Nara, Japan
[78] National and Kapodistrian University of Athens, School of Science, Department of Physics, Athens, Greece
[79] National Centre for Nuclear Research, Warsaw, Poland
[80] National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni, India
[81] National Nuclear Research Center, Baku, Azerbaijan
[82] National Research and Innovation Agency - BRIN, Jakarta, Indonesia
[83] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[84] Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands
[85] Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
[86] Nuclear Physics Institute of the Czech Academy of Sciences, Husinec-Řež, Czech Republic
[87] Oak Ridge National Laboratory, Oak Ridge, TN, United States
[88] Ohio State University, Columbus, OH, United States
[89] Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia
[90] Physics Department, Panjab University, Chandigarh, India
[91] Physics Department, University of Jammu, Jammu, India
[92] Physics Program and International Institute for Sustainability with Knotted Chiral Meta Matter (SKCM2), Hiroshima University, Hiroshima, Japan
[93] Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany
[94] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[95] Physik Department, Technische Universität München, Munich, Germany
[96] Politecnico di Bari and Sezione INFN, Bari, Italy
[97] Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[98] Saga University, Saga, Japan
[99] Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India
[100] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[101] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
[102] Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
[103] SUBATECH, IMT Atlantique, Nantes Université, CNRS-IN2P3, Nantes, France
[104] Sungkyunkwan University, Suwon City, Republic of Korea
[105] Suranaree University of Technology, Nakhon Ratchasima, Thailand
[106] Technical University of Košice, Košice, Slovak Republic
[107] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
[108] The University of Texas at Austin, Austin, TX, United States
[109] Universidad Autónoma de Sinaloa, Culiacán, Mexico
[110] Universidade de São Paulo (USP), São Paulo, Brazil
[111] Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
[112] Universidade Federal do ABC, Santo Andre, Brazil
[113] Universitatea Nationala de Stiinta si Tehnologie Politehnica Bucuresti, Bucharest, Romania
[114] University of Cape Town, Cape Town, South Africa
[115] University of Houston, Houston, TX, United States
[116] University of Jyväskylä, Jyväskylä, Finland
[117] University of Kansas, Lawrence, KS, United States
[118] University of Liverpool, Liverpool, United Kingdom
[119] University of Science and Technology of China, Hefei, China
[120] University of South-Eastern Norway, Kongsberg, Norway
[121] University of Tennessee, Knoxville, TN, United States
[122] University of the Witwatersrand, Johannesburg, South Africa
[123] University of Tokyo, Tokyo, Japan
[124] University of Tsukuba, Tsukuba, Japan
[125] Universität Münster, Institut für Kernphysik, Münster, Germany
[126] Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
[127] Université de Lyon, CNRS/IN2P3, Institut de Physique des 2 Infinis de Lyon, Lyon, France
[128] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg, France
[129] Université Paris-Saclay, Centre d'Etudes de Saclay (CEA), IRFU, Départment de Physique Nucléaire (DPhN), Saclay, France
[130] Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
[131] Università degli Studi di Foggia, Foggia, Italy
[132] Università del Piemonte Orientale, Vercelli, Italy
[133] Università di Brescia, Brescia, Italy
[134] Variable Energy Cyclotron Centre, Homi Bhabha National Institute, Kolkata, India
[135] Warsaw University of Technology, Warsaw, Poland
[136] Wayne State University, Detroit, MI, United States
[137] Yale University, New Haven, CT, United States
[138] Yonsei University, Seoul, Republic of Korea
[139] Zentrum für Technologie und Transfer (ZTT), Worms, Germany
[140] Affiliated with an institute covered by a cooperation agreement with CERN
[141] Affiliated with an international laboratory covered by a cooperation agreement with CERN

[I] Deceased.
[II] Also at: Max-Planck-Institut fur Physik, Munich, Germany.
[III] Also at: Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Bologna, Italy.
[IV] Also at: Dipartimento DET del Politecnico di Torino, Turin, Italy.
[V] Also at: Yildiz Technical University, Istanbul, Türkiye.
[VI] Also at: Department of Applied Physics, Aligarh Muslim University, Aligarh, India.
[VII] Also at: Institute of Theoretical Physics, University of Wrocław, Poland.
[VIII] Also at: An institution covered by a cooperation agreement with CERN.